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Direct photon production at RHIC and LHC energies

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Direct photon spectra and elliptic flow v_2 in heavy-ion collisions at RHIC and LHC energies are investigated within a relativistic transport approach incorporating both hadronic and partonic phases – the Parton-Hadron-String Dynamics (PHSD). The results suggest that a large v_2 of the direct photons – as observed by the PHENIX Collaboration – signals a significant contribution of photons produced in interactions of secondary mesons and baryons in the late stages of the collision. In order to further differentiate the origin of the direct photon azimuthal asymmetry, we compare our predictions for the centrality dependence of the direct photon spectra to the recent measurements by the PHENIX Collaboration and provide predictions for $Pb+Pb$ collisions at LHC energies with respect to the direct photon spectra and $v_2(p_T)$ for 0-40% centrality.

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1. Introduction

Real and virtual photons are powerful tools to probe matter under extreme conditions as created in heavy-ion collisions at relativistic energies, since electromagnetic radiation is emitted over the whole collision evolution. The first several fm/c of the collision are particularly interesting because of the high energy densities reached (well above the expected phase transition region to the deconfined phase). The photons interact only electromagnetically and thus escape to the detector undistorted through the dense and strongly-interacting initially produced medium. Their differential spectra and elliptic flow carry the information on the properties of the matter produced to the detector.

On the other hand, the measured photons provide a time-integrated picture of the heavy-ion collision dynamics and are emitted from every moving charge – partons or hadrons. Therefore, a multitude of photon sources has to be differentiated in order to access the signal of interest. The dominant contributions to the inclusive photon production are the decays of mesons, mainly pions, eta- and omega-mesons. The PHENIX and ALICE Collaborations subtract the "decay photons" from the inclusive photon spectrum using a cocktail calculation [1, 2] and obtain the "direct" photons.

In particular the direct photons at low transverse momentum ($p_T < 3$ GeV) are expected to be dominated by the "thermal" sources, i.e. the radiation from the strongly interacting Quark-Gluon-Plasma (sQGP) [3] as well as secondary meson+meson and meson+baryon interactions [4, 5]. These partonic and hadronic channels have been studied within PHSD in detail in Refs. [6, 7, 8] at Relativistic-Heavy-Ion-Collider (RHIC) energies. It was found that the partonic channels constitute up to half of the observed direct photon spectrum for very central collisions. Other theoretical calculations find a dominant contribution of the photons produced in the QGP to the direct photon spectrum [9, 10, 11].

The low-p_T direct photons probe not only the temperature [1, 2, 12] of the produced QCD-matter, but also its (transport) properties, for instance, the sheer viscosity. Using the direct photon elliptic flow v_2 (a measure of the azimuthal asymmetry in the photon distribution) as a viscometer was first suggested by Dusling et al. in Ref. [13]; this idea was later supported by the calculations in Refs. [11, 12, 14]. It was also suggested that the photon spectra and v_2 are sensitive to the collective directed flow of the system [15, 16] and to the asymmetry induced by the strong magnetic field (flash) in the very early stage of the collision [17, 18].

However, the recent observation by the PHENIX Collaboration [1] that the elliptic flow $v_2(p_T)$ of 'direct photons' produced in minimal bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is comparable to that of the produced pions was a surprise and in contrast to the theoretical expectations and predictions. Indeed, the photons produced by partonic interactions in the quark-gluon plasma phase have not been expected to show considerable flow because they are dominated by the emission in the initial phase before the elliptic flow fully develops.

In Ref. [6] we have applied the PHSD approach to photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and studied the transverse momentum spectrum and the elliptic flow v_2 of photons from hadronic and partonic production channels. A microscopic description of the full collision evolution is done by the covariant off-shell transport PHSD. The degrees of freedom in the partonic and hadronic phases are strongly interacting dynamical quasi-particles and off-shell

hadrons, respectively. Further, it was found in Ref.[7] that the PHSD calculations reproduce the transverse momentum spectrum of direct photons as measured by the PHENIX Collaboration in Refs. [19, 20]. The centrality dependence of the thermal photon yield in PHSD was predicted to be $\sim N_{part}^{\alpha}$ with the exponent $\alpha = 1.5$, which is in a good agreement with the most recent measurement of $\alpha = 1.48 \pm 0.08 \pm 0.04$ by the PHENIX Collaboration [21]. Furthermore, the PHSD also described the data on the elliptic flow of inclusive *and direct* photons. The strong v_2 of direct photons – which is comparable to the hadronic v_2 – in PHSD is attributed to hadronic channels, i.e. to meson binary reactions which are not subtracted in the data. As sources for photon production, we incorporated the interactions of off-shell quarks and gluons in the strongly interacting quark-gluon plasma (sQGP) ($q+\bar{q} \to g+\gamma$ and $q(\bar{q})+g \to q(\bar{q})+\gamma$), the decays of hadrons ($\pi \to \gamma+\gamma$, $\eta \to \gamma+\gamma$, $\omega \to \pi+\gamma$, $\eta' \to \rho+\gamma$, $\phi \to \eta+\gamma$, $a_1 \to \pi+\gamma$) as well as their interactions ($\pi+\pi \to \rho+\gamma$, $\rho+\pi \to \pi+\gamma$, meson-meson bremsstrahlung $m+m \to m+m+\gamma$), meson-baryon bremsstrahlung ($m+B \to m+B+\gamma$) and the two-to-two meson+baryon interactions ($\rho+p \to \gamma+p/n$ and $\rho+n \to \gamma+p/n$) .

The photon production via bremsstrahlung in meson-meson and meson-baryon elastic collisions was found to be an important source for the direct photon spectra and elliptic flow simultaneously [6, 7], where for the calculation of the photon bremsstrahlung from all elastic meson-meson and meson-baryon scatterings m_1+m_2, which occur during the heavy-ion collisions (including $m_i = \pi,\eta,K,\bar{K},K^0,K^*,\bar{K}^*,K^{*0},\eta',\omega,\rho,\phi,a_1$), we have been applying the soft photon approximation. Therefore the resulting yield of the bremsstrahlung photons depended on the model assumptions such as (i) the cross section for the meson-meson elastic scattering (we assumed 10 mb for all meson species), (ii) incoherence of the individual scatterings and (iii) the soft photon approximation (i.e. low photon energy and low $\sqrt{s}$ of the collision). The adequacy of the SPA assumption has been studied in Ref. [22] and a theoretical uncertainty of up to a factor of 2 was found.

The results of our calculations so far have been compared to the data from RHIC. Additionally, here we will provide calculations for the photon production in $Pb+Pb$ collisions as the energy of $\sqrt{s_{NN}} = 2.76$ TeV. Since the preliminary data of the ALICE Collaboration [2, 23] indicate a significant direct photon signal at low p_T with a large elliptic flow at LHC energies, a differential comparison of our calculations with the final data will be mandatory.

2. PHSD

To address the photon production in a hot and dense medium – as created in heavy-ion collisions – we employ an up-to-date relativistic transport model, i.e. the Parton Hadron String Dynamics [24] (PHSD) that incorporates the explicit partonic phase in the early reaction phase. Within PHSD, one solves generalized transport equations on the basis of the off-shell Kadanoff-Baym equations for Greens functions in phase-space representation (in first order gradient expansion, beyond the quasiparticle approximation). The approach consistently describes the full evolution of a relativistic heavy-ion collision from the initial hard scatterings and string formation through the dynamical deconfinement phase transition to the quark-gluon plasma (QGP) as well as hadronization and to the subsequent interactions in the hadronic phase. In the hadronic sector PHSD is equivalent to the Hadron-String-Dynamics (HSD) transport approach [25] that has been used for the description of pA and AA collisions from SIS to RHIC energies and has lead to a fair reproduction of hadron abundances, rapidity distributions and transverse momentum spectra. The description of

quarks and gluons in PHSD is based on a dynamical quasiparticle model for partons matched to reproduce lattice QCD results in thermodynamic equilibrium (DQPM). The DQPM describes QCD properties in terms of single-particle Green's functions (in the sense of a two-particle irreducible approach) and leads to the notion of the constituents of the sQGP being effective quasiparticles, which are massive and have broad spectral functions (due to large interaction rates). The transition from partonic to hadronic degrees of freedom in PHSD is described by covariant transition rates for the fusion of quark-antiquark pairs to mesonic resonances or three quarks (antiquarks) to baryonic states. The PHSD transport approach provides a good description of the data on bulk properties [26] as well as hard probes [27] for a wide range of energies up to the LHC.

3. Direct photon production

We consider the following sources of direct photons:

1) Photons radiated by quarks in the interaction with other quarks and gluons in the two-to-two reactions:

$$\begin{aligned} q+\bar{q} &\to g+\gamma, \\ q/\bar{q}+g &\to q/\bar{q}+\gamma. \end{aligned}$$

The implementation of the photon production by the quark and gluon interactions in the PHSD is based on the off-shell cross sections for the interaction of massive dynamical quasi-particles as described in [6, 28]. In addition, photon production in the bremsstrahlung reactions $q+q/g \to q+q/g+\gamma$ should be incorporated.

2) All colliding hadronic charges (meson, baryons) can also radiate photons by the bremsstrahlung process:

$$m+m \to m+m+\gamma, \tag{3.1}$$
$$m+B \to m+B+\gamma. \tag{3.2}$$

The processes (3.1) have been calculated within the PHSD in Refs. [6, 29], while the $m+B$ bremsstrahlung (3.2) reactions have been added in Ref. [7]. The implementation of photon bremsstrahlung from hadronic reactions in transport approaches so far has been based on the 'soft photon' approximation (SPA) [30], which relies on the assumption that the radiation from internal lines is negligible and the strong interaction vertex is on-shell; this is valid only at low energy (and p_T) of the produced photon.

3) Additionally, the photons can be produced in specific binary hadronic collisions. We consider the direct photon production in the following $2 \to 2$ meson+meson collisions

$$\begin{aligned} \pi+\pi &\to \rho+\gamma, \\ \pi+\rho &\to \pi+\gamma, \end{aligned}$$

accounting for all possible charge combinations. The implementation of these reactions has been described in Refs. [6, 29].

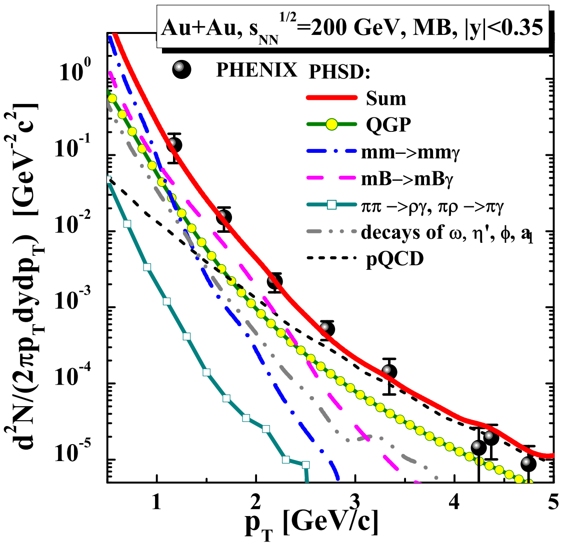

Figure 1: PHSD results for the spectrum of direct photons produced in 0-40% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of the transverse momentum p_T at mid-rapidity $|y| < 0.5$. The data of the PHENIX Collaboration are taken from Ref. [20].

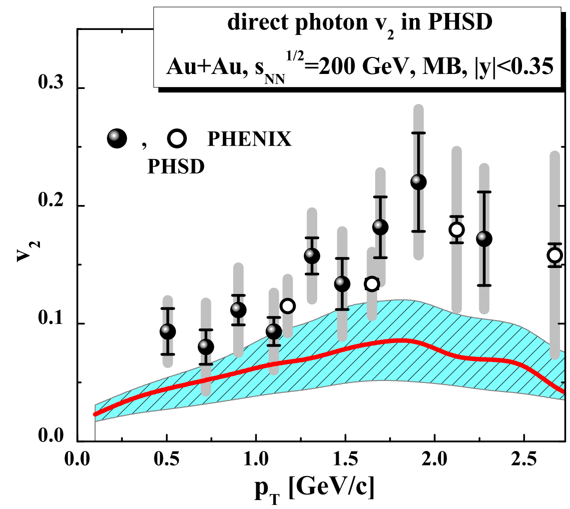

Figure 2: Elliptic flow v_2 versus transverse momentum p_T for the direct photons produced in the minimal bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV calculated within the PHSD (solid red line); the blue band reflects the uncertainty in the modeling of the cross sections for the individual channels. The data of the PHENIX Collaboration are from Ref. [1].

4. Results

The results for the direct photon spectrum as a sum of partonic as well as hadronic sources for the photons produced in 0-40% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is presented in Fig. 1 as a function of the transverse momentum p_T at mid-rapidity $|y| < 0.5$. The calculated channel decomposition of the spectrum is presented in Fig. 1 by the lines of various styles. The measured transverse momentum spectrum dN/dp_T (given by the filled circles) is reproduced well by the sum of partonic and hadronic sources (red solid line).

We find that the radiation from the sQGP constitutes slightly less than half of the observed number of photons. The radiation from hadrons and their interaction – which are not measured separately so far – give a considerable contribution at low transverse momentum. The dominant hadronic sources are the meson decays and the meson-meson bremsstrahlung. While the former (e.g. the decays of ω, η', ϕ and a_1 mesons) can be subtracted from the spectra once the mesonic yields are determined independently by experiment, the reactions $\pi+\rho\to\pi+\gamma$, $\pi+\pi\to\rho+\gamma$, $\rho+p/n\to n/p+\gamma$ and the meson-meson and meson-baryon bremsstrahlung can be separated from the partonic sources only using theoretical models.

The azimuthal momentum distribution of the emitted particles is commonly expressed in the form of Fourier series as

$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n(p_T)\cos[n(\psi-\Psi_n)]\right), \tag{4.1}$$

where v_n is the magnitude of the nth order harmonic term relative to the angle of the initial-state spatial plane of symmetry Ψ_n. One should take into account event-by-event fluctuations

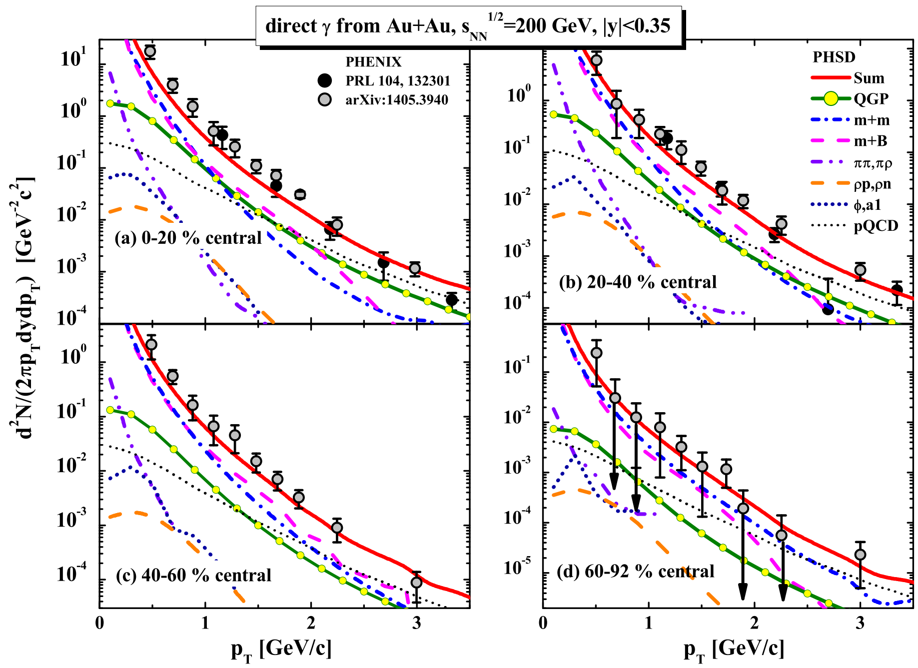

Figure 3: Contribution of the photon production in the two-to-two ρ+nucleon interaction (orange dash lines) to the total direct photon spectra (red lines) at the top RHIC energy of $\sqrt{s_{NN}} = 200$ GeV at different centralities. The dominant sources are the photons from the QGP and from the hadronic two-to-three bremsstrahlung processes. The theory lines – except the ρ+nucleon channel – are taken from the PHSD predictions published in [7]. The PHENIX data are from Ref. [20, 21].

with respect to the event plane Ψ_{EP}. We calculate the v_3 coefficients with respect to Ψ_3 as $v_3\{\Psi_3\} = \langle\cos(3[\psi - \Psi_3])\rangle/\mathrm{Res}(\Psi_3)$. The event plane angle Ψ_3 and its resolution $\mathrm{Res}(\Psi_3)$ are calculated as described in Ref. [31]. We recall that the second flow coefficient v_2 carries information on the interaction strength – and thus on the state of matter and its properties – at the space-time point, from which the measured particles are emitted.

About a decade ago, the WA98 Collaboration has measured the elliptic flow v_2 of photons produced in $Pb+Pb$ collisions at the beam energy of $E_{beam} = 158$ AGeV [32], and it was found that the $v_2(\gamma^{incl})$ of the low-transverse-momentum inclusive photons was equal to the $v_2(\gamma^{\pi})$ of pions within the experimental uncertainties. This observation lead to the conclusion that either (Scenario a:) the contribution of the direct photons to the inclusive ones is negligible in comparison to the decay photons, mainly the π^0 decay products, or (Scenario 2:) the elliptic flow of the direct photons is comparable in magnitude to the $v_2(\gamma^{incl})$, $v_2(\gamma^{decay})$ and $v_2(\pi)$.

However, in view of the WA98 measurement of the direct photon spectrum, which we described above, there is a significant finite yield of direct photons at low transverse momentum. Thus the scenario 1 can be ruled out. Furthermore, the observed direct photons of low p_T must have a significant elliptic anisotropy v_2 of the same order of magnitude as the hadronic flow. This scenario points towards hadronic sources of the direct photons. Thus, the interpretation [29, 33] of the low-p_T direct photon yield measured by WA98 – as dominantly produced by the bremsstrahlung process in the mesonic collisions $\pi+\pi \to \pi+\pi+\gamma$ – is in accord also with the data on the photon

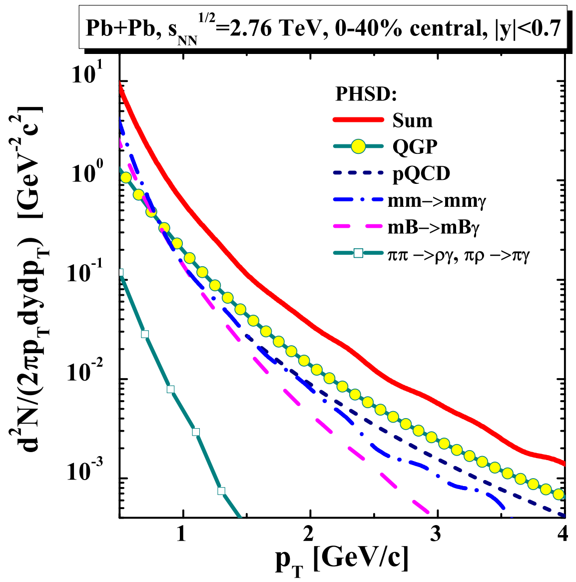

Figure 4: Yield of direct photons in Pb+Pb collisions at the invariant energy $\sqrt{s_{NN}} = 2.76$ TeV for 0-40% centrality as predicted within the PHSD.

elliptic flow $v_2(\gamma^{incl})$.

Let us note that the same conclusions apply also to the most recent studies of the photon elliptic flow at RHIC and LHC. The PHENIX and ALICE Collaborations have measured the inclusive photon v_2 and found that at low transverse momenta it is comparable to the $v_2(p_T)$ of decay photons as calculated in cocktail simulations based on the known mesonic $v_2(p_T)$. Therefore, (a) either the yield of the direct photons to the inclusive ones is not statistically significant in comparison to the decay photons or (b) the elliptic flow of the direct photons must be as large as $v_2(\gamma^{decay})$ and $v_2(\gamma^{incl})$.

In the PHSD, we calculate the direct photon $v_2(\gamma^{dir})$ by building the weighted sum of the channels, which are not subtracted by the data-driven methods, as follows: the photons from the quark-gluon plasma, from the initial hard parton collisions (pQCD photons), from the decays of short-living resonances (a-meson, ϕ-meson, Δ-baryon), from the $2 \to 2$ channels ($\pi + \rho \to \pi + \gamma$, $\pi + \pi \to \rho + \gamma$), and from the bremsstrahlung in the elastic meson+meson and meson+baryon collisions ($m + m \to m + m + \gamma$, $m + B \to m + B + \gamma$). We calculate the direct photon v_2 (in PHSD) by summing up the elliptic flow of the individual channels contributing to the direct photons, using their contributions to the spectrum as the relative p_T-dependent weights, $w_i(p_T)$, i.e.

$$v_2(\gamma^{dir}) = \sum_i v_2(\gamma^i) w_i(p_T) = \frac{\sum_i v_2(\gamma^i) N_i(p_T)}{\sum_i N_i(p_T)}. \tag{4.2}$$

The results for the elliptic flow $v_2(p_T)$ of direct photons produced in $Au + Au$ collisions at the top RHIC energy are shown in Fig. 2. According to our calculations of the direct photon spectra, almost a half of the direct photons measured by PHENIX stems from the collisions of quarks and gluons in the deconfined medium created in the initial phase of the collision. The photons produced in the QGP carry a very small v_2 and lead to an overall direct photon v_2 about a factor of 2 below the pion

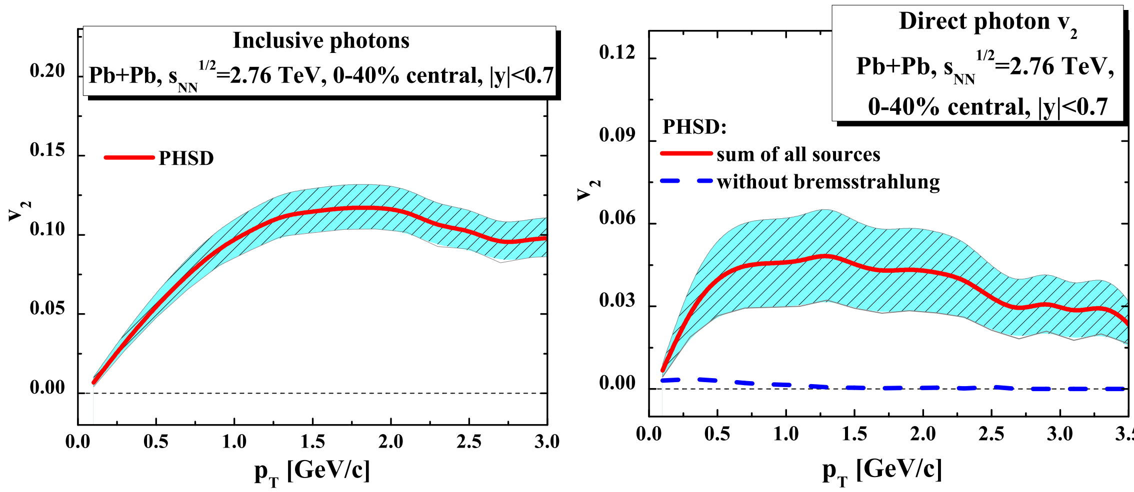

Figure 5: Left: Elliptic flow v_2 versus transverse momentum p_T for the inclusive photons produced in 0-40% central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as predicted by the PHSD (solid red line); the blue error band reflects the finite statistics and the uncertainty in the modeling of the cross sections for the individual channels. **Right:** Elliptic flow v_2 versus transverse momentum p_T for the direct photons produced in 0-40% central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as predicted by the PHSD (solid red line); the blue error band is dominated by the uncertainty in the modeling of the cross sections for the individual channels.

$v_2(\pi)$ even though the other channels in the sum (4.2) have large elliptic flow coefficients v_2 of the order of $v_2(\pi)$ (cf. Ref. [6]).

Indeed, the parton collisions – producing photons in the QGP – take place throughout the evolution of the collision but the collision rate falls rapidly with time and thus the production of photons from the QGP is dominated by the early times (cf. Fig. 7 in Ref. [6]). As a consequence, the elliptic flow 'picked up' by the photons from the parent parton collisions saturates after about 5 fm/c and reaches a relatively low value of about 0.02, only. We note that a delayed production of charges from the strong gluon fields ('glasma' [34]) might shift the QGP photon production to somewhat later times when the elliptic flow is built up more. However, we cannot quantitatively answer whether the additional evolution in the pre-plasma state could generate considerable additional v_2.

In addition, the centrality dependence of the direct photon spectra and flow has been investigated. The recent measurements by the PHENIX Collaboration [21] confirm the predictions within the PHSD from Ref. [7]. We present our predictions and the data in Fig. 3. The centrality dependence of the integrated thermal photon yield in PHSD was found to scale as N_{part}^{α} with the exponent $\alpha = 1.5$, which is in a good agreement with the most recent measurement of $\alpha = 1.48 \pm 0.08 \pm 0.04$ by the PHENIX Collaboration [21].

Centrality dependence of the direct photon elliptic flow v_2 was also calculated within the PHSD in Ref. [7] and confirmed (within the error bars) by the PHENIX Collaboration measurements in Ref. [20, 21]. Thus the observed centrality dependence of the elliptic flow is in agreement with the interpretation of the direct photons having a hadronic origin (in particular from the bremsstrahlung in meson+meson and meson+baryon collisions), which is stronger in more peripheral collisions.

In Fig. 4 we show the calculated direct photon yield in Pb+Pb collisions at the invariant energy $\sqrt{s_{NN}} = 2.76$ TeV for 0-40% centrality. Comparing the theoretical predictions to the preliminary

data of the ALICE Collaboration from Ref. [2], we find an overall agreement with the data within about a factor of 2 in the range of transverse momenta p_T from 1 to 4 GeV. On the other hand, the calculations tend to underestimate the preliminary data in the low-p_T region and to underestimate slightly the highest-p_T points. One cannot exclude the existence of another yet unknown source of direct photons at low p_T. However, the significance of the comparison is not robust untill the final data will be available.

We finally present our predictions for the elliptic flow of inclusive and direct photons produced in $Pb+Pb$ collisions at the energy of $\sqrt{s_{NN}} = 2.76$ TeV at the LHC within the acceptance of the ALICE detector. Fig. 5 (left hand side) presents predictions for the elliptic flow v_2 versus transverse momentum p_T for the *inclusive* photons produced in 0-40% central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (solid red line) with the blue error band reflecting the finite statistics and the theoretical uncertainty in the modeling of the cross sections for the individual channels. Finally, the elliptic flow $v_2(p_T)$ of *direct* photons produced in 0-40% central Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV –as predicted by the PHSD (solid red line) – is shown in Fig. 5 (right hand side); the blue error band is dominated by the uncertainty in the modeling of the cross sections for the individual channels. The lines presented in Fig. 5 will have to be compared to the future experimental data in order to shed further light on the direct photon sources and production mechanisms.

5. Summary and outlook

In this contribution we have calculated the momentum spectra and the elliptic flow v_2 of direct photons produced in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in $Pb+Pb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the microscopic PHSD transport approach. For photon production we have incorporated the interactions of quarks and gluons in the strongly interacting quark-gluon plasma (sQGP) ($q+\bar{q} \to g+\gamma$ and $q(\bar{q})+g \to q(\bar{q})+\gamma$), the photon production in the hadronic decays ($\pi \to \gamma+\gamma$, $\eta \to \gamma+\gamma$, $\omega \to \pi+\gamma$, $\eta' \to \rho+\gamma$, $\phi \to \eta+\gamma$, $a_1 \to \pi+\gamma$) as well as the interactions ($\pi+\pi \to \rho+\gamma$, $\rho+\pi \to \pi+\gamma$, and the bremsstrahlung radiation $m+m/B \to m+m/B+\gamma$) of mesons and baryons produced throughout the evolution of the collision.

We find that the PHSD calculations reproduce the transverse momentum spectrum of direct photons as measured by the PHENIX Collaboration in Refs. [19, 20]. The calculations reveal the channel decomposition of the observed direct photon spectrum and show that the photons produced in the QGP constitute at most about 50% of the direct photons with the rest being distributed among the other channels: mesonic interactions, decays of massive hadronic resonances and the initial hard scatterings. Our calculations demonstrate that the photon production in the QGP is dominated by the early phase (similar to hydrodynamic models) and is localized in the center of the fireball, where the collective flow is still rather low, i.e. on the 2-3 % level, only. Thus, the strong v_2 of direct photons - which is comparable to the hadronic v_2 - in PHSD is attributed to hadronic channels, i.e. to meson and baryon binary reactions. On the other hand, the strong v_2 of the 'parent' hadrons, in turn, stems from the interactions in the QGP via collisions and the partonic mean-filed potentials. Accordingly, the presence of the QGP shows up 'indirectly' in the direct photon elliptic flow. In the future, we plan to (i) go beyond the soft photon approximation (SPA) in the calculation of the bremsstrahlung processes $meson + meson \to meson + meson + \gamma$, $meson + baryon \to meson + baryon + \gamma$ and (ii) will quantify the suppression at low p_T due the Landau-Migdal-Pomeranchuk (LMP) effect.

The centrality dependence of the direct photon production the potential to further clarify the direct photon production mechanisms. We find a good agreement between the PHENIX measurements and PHSD calculations. In particular, the integrated thermal photon yield in PHSD was predicted to scale as N_{part}^{α} with the exponent $\alpha = 1.5$, which is in good agreement with the most recent measurement of $\alpha = 1.48 \pm 0.08 \pm 0.04$ by the PHENIX Collaboration [21]. This observation supports the conclusion that the low transverse momentum direct photons have a strong contribution from the binary hadronic photon production sources, such as the $meson + meson$ and $meson + baryon$ bremsstrahlung. It will be important to investigate experimentally the scaling of the direct photon yield and flow with the number of participating nucleons N_{part} at LHC, too.

Acknowledgments

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